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Design and performance evaluation of a coarse/fine precision motion control system

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Abstract
This abstract presents current collaborative work on the development of a stage system for accurate nanometer level positioning for scanning specimens spanning an area of 50 mm × 50 mm. The completed system employs a coarse/fine approach which comprises a short-range, six degree-of-freedom fine-motion platform (5 microns 200 micro-radians) carried by a long-range, two-axis *X*-*Y* coarse positioning system. Relative motion of the stage to a fixed metrology frame will be measured using a heterodyne laser in an eight-pass interferometer configuration. The final stage system will be housed in a vacuum environment and operated in a temperature-controlled laboratory. Results from a simple single coarse/fine axis system will be the design basis for the final multi-axis system. It is expected that initial stage performance evaluation will be presented at the conference.

Introduction
The motivation for this project is to help facilitate the transition from nano-science to productive nanotechnology. The current system will provide the ability to “pick and place” at nanometer levels and compare system performance with other similar designs at international locations such as, National Physical Laboratory (NPL) in the UK, Technical University of Eindhoven (TUE) in the Netherlands and Physikalisch-Technische Bundesanstalt (PTB) in Germany. It is envisaged that the system will be used for long range scanning of specimens (including biological), micro- /macro-assembly, imprint lithography and as a coordinate measuring machine (CMM).
Major objectives of this project include;

- Development of integrated position measurement system with nanometer uncertainties traceable to national standards.
- Translation mechanism for multi degree-of-freedom motion control.
- Integration of fine motion controllers into long-range instrumentation for nano-scale manipulation in centimeter-sized workspaces.
- Integration of cascaded multi degree-of-freedom control systems.

Critical requirements of the system are as follows;

- Vacuum Compatibility of better than 13 mPa (10^{-4} Torr)
- Range of 50 mm $\times$ 50 mm $\times$ 5 microns
- Maximum translation velocity of 5 mm$\cdot$s^{-1}
- Resolution of better than 1 nm
- Accuracy of 10 nm.

Single axis coarse/fine prototype

Figure 1 shows a line diagram of the single axis stage developed to assess the performance and functionality of the coarse/fine approach. The coarse stage carriage housed five kinematically positioned ultra-high molecular weight polyethylene (UHMWPE) thin-film bearings [1] that slides on two parallel Zerodur™ flat guide-ways. The UHMWPE bearing is based on the thin-film PTFE bearing used in precision instruments such as the Tetraform™ grinding machine [2], Nanosurf II [3] and the Nanosurf IV [4] profilometers. In addition to gravity load, a simple flexure mechanism is implemented to provide the desired normal preload. To constrain the carriage in a yaw motion, another flexure mechanism is rigidly attached to the carriage to provide continuous contact between the UHMWPE bearing and Zerodur™ optical flat. The fine stage is a single-degree-of-freedom (SDOF) flexure driven by a preloaded 20 millimeters PZT stack. The fine stage has a stroke of 17 microns which is primarily used to compensate the translation error of the coarse stage. A mirror is glued to the fine stage to provide the measurement arm feedback of a two pass displacement measuring interferometer. Performance results of the one axis system are shown in Figure 2.

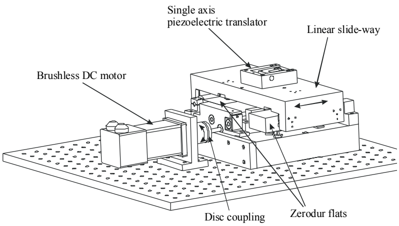
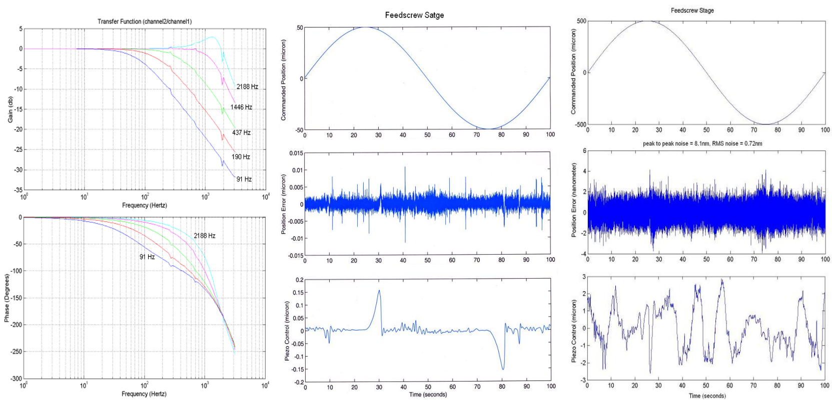


Figure 1: Line diagram of the single axis coarse/fine stage.



(a) (b) (c)

Figure 2: a) Bandwidth of the fine motion stage at various gains. Ideally, a high bandwidth is desired so that the error compensation can be maximized. b) Control signals during a demanded sinusoidal displacement of 50 microns, upper trace is the commanded position, middle trace is the error signal to the controller and lower trace corresponds to the voltage applied to the amplifier of the piezoelectric actuator and corresponds to the full scale displacement of 7 microns. c) Trace after tuning of controller at a sinusoidal displacement of 500 microns. The fine stage gain is 600 corresponding to 2188 Hz. This yields a peak-to-peak noise of 8.1 nm and a RMS noise of 0.72 nm. To minimize the errors, the PZT command must continuously work hard.

Multi-axis coarse/fine design

Following the single axis prototype, a multi-axis stage system has been designed to scan a 50 mm x 50 mm area with a fine stage that will compensate for errors in six degrees-of-freedom. Based on observations and performance data obtained from the single axis stage, a number of modifications will be made to reduce the overall size of the system and enhance system performance. These include:

- Redesign the wobble pin drive coupling mechanism between the feedscrew nut and long range carriage to a string/thin-rod in tension to accommodate for both vertical and horizontal motion and torsional forces introduced by the drive mechanism.
- Replace the horizontal preload mechanism that maintains the vertical carriage guide bearings in contact with the slideway surface with a single UHMWPE bearing for space savings and reduce noise generated by the roller bearing.
- Integrate two Aerotech frameless DC motor for the feedscrew drives in both axes.
- Further refine the flexures for support of the optical flat slideway references.

The fine phase of the multi-axis system is a second generation platform depicted in Figure 3 with displacement capabilities of approximately 5 microns and rotations of 200 micro-radians. The figure shows comparisons between the first and second generation fine-motion stage systems with and without damping. From this graph and other performance tests, a bandwidth up to 170 Hertz was observed. In comparison to the observation of the single axis system, it is apparent that improvements in dynamic performance of the fine stage are necessary to enhance the overall system performance. To achieve this, a third generation was designed incorporating more damping by increasing the damping areas and reducing mass to compensate for the weight of the specimen stage. It is expected that results of this third generation fine motion stage will be presented at the conference.

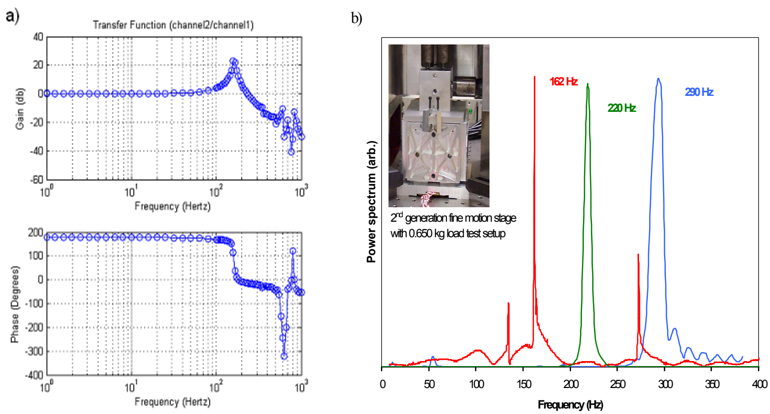


Figure 3: Stage performance: a) Response of the *y* coordinate to an input in the same direction. b) Poles I and II, 1st and 2nd generation stage with 0.650 kg load, respectively. Poles III shows the 2nd generation with no load.

In contrast to the single axis system, the multi-axis system will incorporate a high-speed eight-pass heterodyne displacement measuring interferometer. The modular optics for beam splitting and recombination will be mounted orthogonal to each other while two orthogonal mirrors mounted on the specimen stage provide the feedback of the measurement arms. The interferometer system measures displacement in x and y and rotation about the z-axis while three capacitance sensors collinear to the z-axis provide displacement in z and rotations about the x and y axes. A solid model of the complete system is shown is Figure 5. The stage controller block diagram is shown in Figure 6. As shown in the diagram, at the highest level the controller is responsible for coordinating fine and coarse motion along with taking images from probe systems associated with the stage. The fine motion stage will be implemented with a six-axis piezoelectrically actuated stage with a range of 5 microns and 200 micro-radians in each axis. Motion of this fine stage will be measured with the combine interferometer and capacitance sensor system.

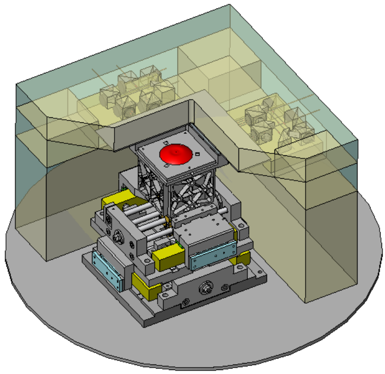


Figure 5: Solid model of complete system.

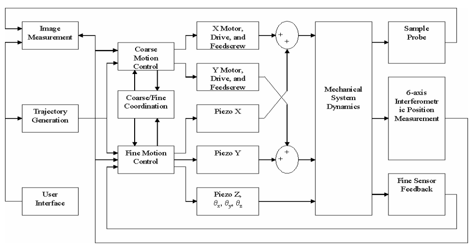


Figure 6: Block diagram of system control architecture for the multi-axis coarse/fine stage.

The coarse stage system provides x- and y-motion over long travel (about 50 mm) via two feed-screws driven with brushless DC frameless motors with integral encoders. The controller will coordinate the motion of these two stage systems so as to remain within the limited travel of the fine stage while achieving nanometer-scale resolution over the full travel of the coarse stage.

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